Measuring Strain Concentrations in Welded Junctions using Digital Image Correlation

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Abstract—**The utilization of different welding processes as a joining technique in the construction of systems and structures is widespread in the industry nowadays. Most welding processes entail the creation of a bead of filling material that protrudes from the jointed material. This welding bead generates a pronounced geometry change and, consequently, a strain rising localization at the toe of the aforementioned weld bead.**

Many approaches have been adopted to measure strain concentrations (SC) in different types of welded junctions. The most common technique is the use of strain gauges, located at specified distances from the SC zone, and posterior application of extrapolation algorithms with the measured values. The use of this technique has some limitations due to the strain gauge characteristics, impeding its installation at material discontinuities and thereby compelling to perform an extrapolation process. Additionally, it is impossible to know a priori the exact location of the maximum strains, leading to possible errors due to inaccurate location of the strain gauges. In order to overcome these limitations, Digital Image Correlation (DIC) is presented as a very valuable alternative. DIC enables to measure the strain field along the whole region of interest. As such, this full-field measuring technique ensures to capture the maximum strains, which eliminates the need for extrapolation methods.

For the present work, three welded steel plates were fabricated and subjected to tensile load in order to measure the strain fields at the weld toe and its vicinity. Loads were applied ensuring elastic deformation of the specimen.

Prior to image correlation, a study of the limitations of DIC when measuring heterogeneous strain fields in the elastic range was carried out, which resulted in a number of recommendations with respect to the correlation parameters.

All experimentally acquired images were then post processed using these findings. Finally, the SCFs along the weld were determined and significant variations were observed. The latter suggests an influence of the local geometrical features of the weld bead.

The experimental characterization of the SC in welded junctions presented in this work supposes a valuable tool for structural designers and analysts. Indeed, it enables to determine the actual maximum strain present in the welded junction which can be of use for simplified models. Also, a novel method for experimentally obtaining SC is introduced in the present article.

I. INTRODUCTION

Welding processes are a very common technique used in the construction and assembly of metal structures nowadays. Although the different welding techniques have been largely improved through the last decades, most of these techniques imply the utilization of filling material which will protrude from the jointed material after the welding process. The resulting weld bead, will generate a strong change in the geometry of the junction, leading to strain concentrations at the toe of the aforementioned weld bead.

When a welded structure is subjected to working loads, the magnitude of the SC of the junctions will dictate its failure. Therefore, measurement and characterization of these regions becomes crucial in structural analysis and design of welded structures. Consequently, significant efforts have been made on experimentally determining the SC on different welded junctions. The most widely adopted parameter to evaluate the SC is the strain concentration factor (SCF). The SCF is defined as the ratio between the maximum local strain measured and the nominal strain, i.e. not considering local geometry discontinuities or changes. The most commonly used technique for the determination of the SCF is by using strain gauges located at controlled distances from the strain concentration zone and posterior application of extrapolation algorithms with the measured values. R. M. Fidelis, X-L. Zhao and P. Grundy [1] evaluated the stress concentration factors of welded T-joints under in-plane bending, using strain gauges and second order polynomial extrapolation techniques. Similarly, W. M. Gho and F. Gao [2] used strain gauges placed at specific locations to develop a parametric formulae for the SCF in overlapped tubular joints.

The use of strain gauges for measuring strain concentration has some inherent limitations. First, the dimensional features of strain gauges hamper their installation at locations with strong geometrical changes, which coincide with the strain concentration zones in welded junctions, thus requiring extrapolation techniques to estimate the maximum actual strain. Second, due to the nature of the weld geometry, it is not possible to know in advance the exact location of the maximum strains, where failure is most likely to occur. Inaccurate installation of the strain gauges inevitably leads to inaccurate determination of the SCF. To overcome these drawbacks, Digital Image Correlation (DIC) [3] presents itself as a very valuable alternative, since it enables to determine the strain over a complete region of interest.

This non-contact full-field measuring technique subjects digital images taken of an object before and after loading to a correlation algorithm to yield displacements and strain fields.

Different approaches have been proposed to measure strain concentrations with DIC: Š. František, Š. Michaela and H. Martin [4], for instance, analyzed in-plane stress concentration in a holed specimen using two dimensional DIC. In a slightly different field of application, S-H. Tung and C-H. Sui [5] used image correlation techniques to measure strain distributions in cracked cylindrical pipes subjected to increasing internal pressure loads.

Although diverse research studies have been carried out regarding measurements of strain concentrations using DIC, most of them are limited to 2D DIC and usually do not assess the correlation parameters used for these calculations. When measuring heterogeneous deformation fields, as is the case of strain concentrations, DIC testing conditions and image processing settings become crucial in order to achieve accurate results [6], [7].

Present work aims to characterize the strain concentration along different weld toe profiles using DIC in the elastic range of deformation, i.e. deformations below yield strain. To this purpose, three welded specimens where fabricated and subjected to uniaxial loading in a standard tensile machine. Each side of the weld bead of every specimen was tested separately since the required camera positioning for accurately capturing the weld toe profile hampered focusing both weld toe profiles in a single picture. A total of 20 images of each weld profile were taken of the loaded specimen for statistical assessment of the results. Prior to the correlation process, the optimal correlation parameters were investigated.

The actual experiments were then post processed using the obtained optimal settings. Afterwards, the evaluation of strain concentration along the weld toe was carried out. To this aim, the strain concentration factor (SCF) parameter was utilized, calculated as the ratio between the strain values at the weld toe, and the nominal strain, located out of the influence of any strain concentrations

As it will be discussed in greater detail in the results section, significant variation of the SCF along the weld toe was observed, suggesting a large influence of local geometrical characteristics of the weld bead.

The study developed in this article introduces a novel technique for measuring strain concentration in welded junctions with clear advantages with respect to the conventional strain gauges. Also, valuable results have been obtained concerning the characterization of strain concentrations in welded junctions.

II. Test Description

As stated before, three welded junctions were used for this study, all of them subjected to uniaxial tensile loads. The specimen and testing characteristics will be explained in more detail in the following subsections.

A. Specimen characteristics

Figure 1 shows the dimensions of the welded specimens used in this study. Base material of the specimen is S275JR. All the welds have been performed using MIG welding technology, with filler material recommended for this type of steel according to standard UNE-EN 13479.

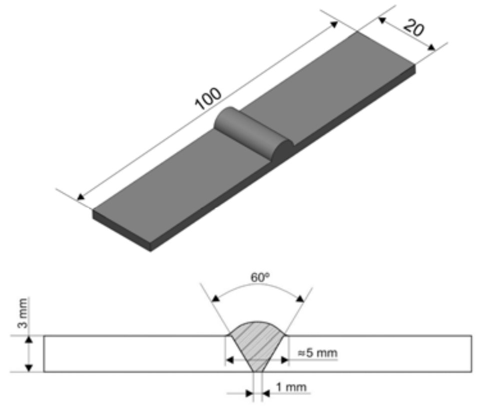


Figure 1. Specimen dimensions (mm).

Joint preparation was carried out according to standard UNE-EN ISO 9692-1.

The DIC algorithm needs a random contrast pattern in order to compare unique discrete grayscale function between reference and deformed image. To this purpose, a random speckle pattern has to be attached to the specimen surface, usually with ordinary paint stray. Typically, the surface is first coated with white matt paint. After that, a black random speckle is applied. shows one of the specimens after random speckle pattern application.

B. Experiment set up

The specimens were subjected to 10kN uniaxial load. For that, a Zwick Z010 Tensile testing machine was utilized. The setup of the specimens and the cameras is shown in the Figure 3. As it can be inferred, the cameras focus the specimen slightly from the top in order to capture the weld toe profile clearly. This configuration impedes viewing both weld toes in the same picture; therefore, each specimen had to be tested twice, turning the clamping position 180º one with respect to the other. This allowed testing the specimens without changing the cameras setup, which could introduce variability in the results.

Twenty images were taken of each side of the specimen when loaded to check stability of the image processing and results.

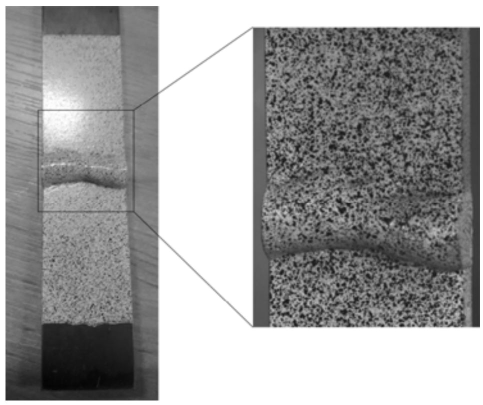


Figure 2. Specimen after surface painting.

Figure 3 Experiment setup

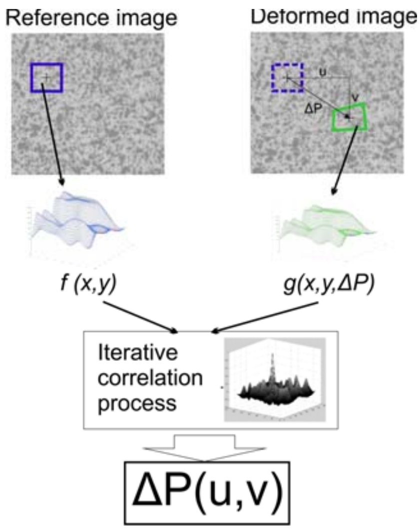


Figure 4 Image correlation process

III. IMAGE PROCESSING SETTINGS

A. DIC basics

For a better understanding of the different parameters used in image processing, some DIC basics are introduced in this section. For simplicity, and since the theoretical principles are identical, DIC basics will be illustrated for the case of 2D image correlation. The displacement calculation process from the acquired pictures is shown schematically in . First, the reference image is divided in small squares of *NxN* pixels called subsets. For each subset, a grayscale function is constructed (*f(x,y)*), usually based on bilinear, bicubic polynomial interpolators or bicubic splines. On the basis that the subset positions in the reference and deformed images are related via a transformation function (*f(x,y)=g(x,y,ΔP)*), an iterative correlation process runs until the desired correlation coefficient is met. Correlation coefficient is typically calculated utilizing cross correlation functions; an example is the normalized cross correlation criterion, which reads as (1):

$$NCC = \frac{\sum f_{(x,y)} g_{(x,y,\Delta P)}}{\sqrt{\sum f_{(x,y)}^2 \sum g_{(x,y,\Delta P)}^2}} \tag{1}$$

The order of the abovementioned transformation function can vary depending on the deformed subset shape complexity. The simplest zero-order functions only consider rigid body displacement of the subset, whereas second-order terms are able to accounts for shape changes (e.g. bending), suitable of heterogeneous deformation fields as is the case of strain concentrations.

The correlation process is halted once the correlation coefficient is met for every subset. Although each pixel of the picture can be accounted for the image correlation, it is common to use information of less pixels (e.g. every 3, 7, 10, etc.) in order to save computational costs. The number of pixels skipped is known as *Stepsize*.

The strain calculation in DIC can be understood as a post-processing operation. It is calculated from the displacement field as the first order derivative. To that purpose a first or second order polynomial is fitted to the displacement data along the Virtual Strain Gauge (VSG).

The VSG is expressed in mm and reads as (2), where, *SW* (Strain Window), is the number of pixels used for the displacement fitting function, *Ss* is the *Stepsize,* and *Ps* is the pixel size in mm.

$$VSG(mm) = \left[\left(SW - 1 \right) Ss + 1 \right] Ps \tag{2}$$

B. Processing settings

In the previous section the main correlation parameters to be configured in DIC have been outlined. The optimum parameter values to be chosen vary depending on the specimen shape nature, the deformation complexity and the accuracy desired. The conditions of the case studied in this work corresponds to small strains (elastic range) and very heterogeneous fields (strain concentrations), therefore the parameters must be set cautiously in order to achieve accurate results and avoid smoothing strains, especially along highly heterogeneous zones.

In heterogeneous displacement fields, the subset size is recommended to be as small as possible in order to reproduce the displacement changes accurately. Unfortunately, the minimum size of the subset is determined by the speckle dimensions; generally, the subset should be at least as large as the biggest blob of the speckle pattern. A subset of 25x25 pixels was adopted in consideration of these limitations. Also, quadratic subset transformation function was utilized to better adapting to the high displacement gradient zones.

The VSG size becomes of vital importance when calculating heterogeneous strain fields, especially in the elastic range: too small VSG will lead to too noisy results, and too large ones will tend to smooth strain concentrations. According to equation (2), the smaller the pixel size, the bigger the *SW* and *Ss* can be without increasing the *VSG*, and therefore, less noisy results will be obtained. For this reason, obtaining a small pixel size was a key condition for the experiment setup. It was achieved a final pixel size of 19.3 µm.

With the purpose of assessing the accuracy and noise of the calculations for different values of *VSG*, the same image was processed utilizing different combinations of *SW* and *S* to obtain a VSG size range between approximately 0.4 mm to 2.25 mm. Then, the mean strain value and the standard deviation over a homogeneous deformation region were extracted. As can be inferred from the results shown in Figure 5, the strain values converge from a VSG size of around 1mm. The standard deviation of the strains decrease rapidly for small VSG's, but from values of about 1.5 mm the improvement is less significant.

Although it is not possible to know a priori the size of the strain field shape along concentration zone, according to the results obtained in the experimental study, it was decided to use a VSG of 1.75 mm, which corresponds to Ss=3 and SW=31. Additionally, second order polynomial was used to fit the displacements in the VSG as it can reproduce sharp displacement variations more accurately.

IV. SCF CALCULATION METHODOLOGY

Having established the processing settings to be used for image correlation, the strain fields of both weld sides of each specimen were calculated.

As stated before, the SCF is calculated as the ratio between the maximum actual strain at the weld toe, and the nominal strain out of the influence of any strain concentration. The calculation process is schematized in Figure 6: at every X direction increment, the strain profile was extracted and the maximum strain value obtained. Although the nominal strain is supposed to be constant over X direction, minimum misalignments during the specimen installation can lead to small variations of the strain along this direction. For this reason, only nominal strains with the same X coordinate as the maximum strain where taken into account for the SCF calculation.

Due to the loss of information at the borders of the region of interest in DIC during the deformation of the specimen, data very close to these limits can produce inaccurate results. For this reason, these data were excluded from the SCF calculation.

Due to the irregular geometry of the weld toe profile, it was not always possible to light and focus it in the best conditions. These zones usually give poor correlation coefficients. Therefore, to ensure accurate results, strain calculations out of data belonging to correlation coefficients below 0.9 were not considered in the SCF determination process.

V. RESULTS

The SCF obtained following the procedure described in the previous section are shown in , where the SCF evolution along the six weld toe profiles tested (two weld bead sides per specimen, A and B respectively) can be observed. The black line represents the mean value of the SCF along each profile for the twenty images taken at the same load case, and the blue lines represent the upper and lower limits for ± two standard deviations. The gaps along the profiles belong to data discarded due to correlation coefficient under 0.9.

As it can be noticed, there is a significant variability of the SCF along the weld toe profiles. This fact is evidenced by the notable standard deviation, which is approximately 0.37 in all profiles, with the exception of the profile 'B' of specimen 3 where it becomes higher due to the increasing tendency of the SCF.

Figure 8 shows the overall SCF histogram, as well as SCF values for increasing cumulative probabilities. The overall mean and standard deviation of the SCF are 2.36 and 0.54 respectively, resulting in a relative standard deviation of 22.9%, illustrating again the scatter of the SCF. As indicated in the figure, only 10% of the SCF calculated present values under 1.56. On the other hand, 90% of the SCF values are under 3.07. In total, 1033 SCFs where computed at different positions of the welded junctions tested.

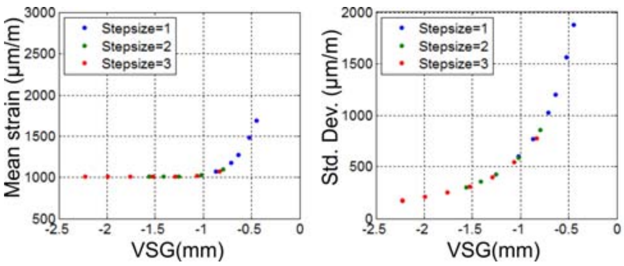


Figure 5 Mean strain and standard deviation over a homogeneous deformation region.

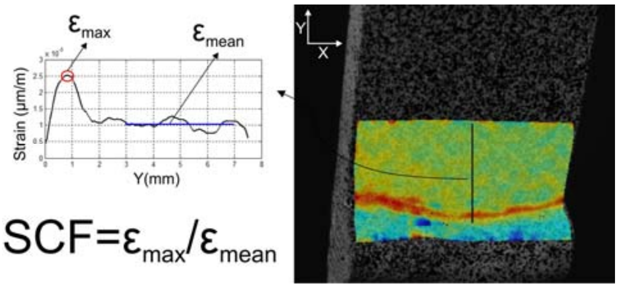


Figure 6 SCF calculation methodology.

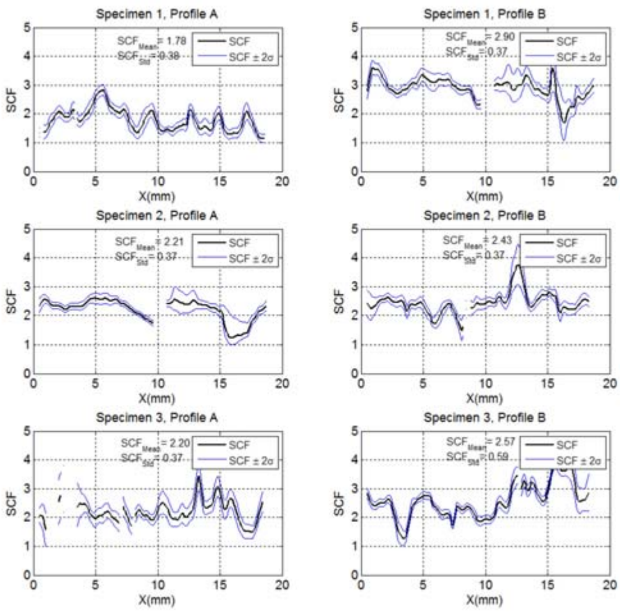
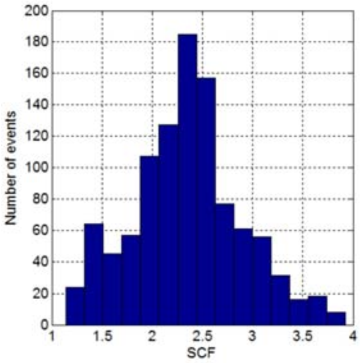


Figure 7 SCF of each specimen and weld bead side.



Probability (%)	SCF
10	1.56
20	1.92
30	2.08
40	2.24
50	2.36
60	2.45
70	2.56
80	2.76
90	3.07

Figure 8 Probability study of the SCF

VI. CONCLUSIONS

In the present work the DIC technique has been introduced as an alternative tool to measure strain concentrations in welded junctions. Recommendations with respect to a proper use of the technique when measuring strain concentrations are given. It has been shown that achieving a small pixel size in these circumstances is of utmost importance. In addition, large influence of the DIC image processing settings on the final results has been demonstrated.

Two main advantages of using DIC for strain concentration measurements with respect to strain gauges have been illustrated. First, full strain fields have been obtained, enabling to avoid any extrapolation process to determine maximum strains (necessary when using strain gauges). Second, a total of 1033 SCFs have been calculated at different positions of the specimen's weld toes ensuring to obtain the maximum strain concentrations in the junction. Clearly, this is not possible when using strain gauges.

Although a pixel size of less than 20 µm seems to be small enough to accurately characterize the strain field along the concentration zone, it must be pointed out that additional studies are required to fully assess the smoothing effect along these regions.

The results obtained suggest that local geometry characteristics of the weld bead have great influence on the SCF. Future work will focus on the study of the relation between different geometric features and the SCF.

Additionally, the results presented in the article are a valuable tool for the analysis of welded structures as the method enables to determine the actual strain experienced by welded junctions in simplified structure models. Also, the results of the probability study presented allow choosing different SCF values according to different probability of occurrence and the required safety level.

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